Silicon (2025) 17:377–390
https://doi.org/10.1007/s12633-024-03202-6

RESEARCH

Silicon and Potassium Fertilization Upgrade Resilience in Bell Pepper against Salt Stress through Boosting Root Growth and Fruit Yield

Fabiha Bushra[1] · Disha Mallick[1] · Md. Bappy Hossain[1] · Sumon Chandra Pal[1] · Prosanta Kumar Dash[1] · Nure Kutubul Islam[2] · Md. Abdul Mannan[1] · Debesh Das[1]

Received: 3 July 2024 / Accepted: 16 November 2024 / Published online: 5 December 2024

Abstract

Bell peppers are highly sensitive to salt stress, posing significant challenges for sustainable vegetables production especially bell pepper under suboptimal climatic conditions. Given the economic importance of bell peppers, enhancing their tolerance to salinity stress is a critical research focus over period. Silicon (Si) and potassium (K) and are crucial elements that have potential to combat salt stress significantly. This study aimed to investigate influential role of Si and K fertilization on root growth, physiological response, and fruit yield of bell pepper under salt stress. The factorial experiment included six fertilizer doses (F_0: control- recommended fertilizer dose (RDF); F_1: RDF + K_{30} (35 kg ha^{-1} K); F_2: RDF + 60 kg ha^{-1} Si (soil); F_3: RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil); F_4: RDF + 100 ppm Si (foliar), and F_5: RDF + K_{30} (35 kg ha^{-1} K) + 100 ppm Si (foliar) and five water salinity levels (control- 0.54, 3, 6, 9, and 12 dS m^{-1}). Results revealed that root morphological traits particularly root biomass, root-shoot ratio, root length and root length density were significantly improved by RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil), followed by RDF + K_{30} (35 kg ha^{-1} K) + 100 ppm Si (foliar). At 12 dS m^{-1} salinity level, about 53% and 55% higher root and shoot biomass was reported at RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) in compare to control. Leaf proline accumulation was increased with rising salinity levels which maximized by 51% at RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) followed by 43% increase at RDF + K_{30} (35 kg ha^{-1} K) + Si (foliar) over control at 12 dS m^{-1} salinity level. Enhanced fruit yield was observed with various Si and K fertilization combinations, where RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) shown a 62% and 40% higher yield in compare to control at 9 and 12 dS m^{-1} salinity levels, respectively. Collectively, incorporating Si and K with standard fertilizer demonstrated synergistic effects, to mitigate the adverse impacts of salt stress through up-regulating root-shoot morphological traits, physio-biochemical attributes and fruit yield of bell pepper.

Keywords Salt stress · Silicon · Root biomass · Proline · Fruit yield

1 Introduction

Bell pepper (*Capsicum annuum* L.), a crucial vegetable from the Solanaceae family, holds significant market demand due to its nutritional qualities but very much sensitive to salt stress [1]. Soil salinity is a major abiotic stressor that disrupts bell pepper growth and yield by impairing the plant's ability to absorb water and nutrients. Salt stress induces physiological changes, including the accumulation of toxic ions and reactive oxygen species (ROS), which damage cellular structures and macromolecule synthesis. Salinity severely reduces root growth and nutrient uptake [2]. Maintaining soil health, fertility, and productivity is increasingly important in the context of global climate change, which exacerbates soil salinization [3–5]. Enhancing root growth, physiological responses, and fruit yield through efficient nutrient management is crucial for sustainable bell pepper production under salt stress. The combined use of silicon (Si) and potassium (K) is a promising option for improving root growth and fruit yield in saline conditions.

Silicon is a bioactive quasi-essential element that is absorbed by plants as monosilicic acid. It enhances soil

---

✉ Debesh Das
debeshdasat@at.ku.ac.bd

[1] Agrotechnology Discipline, Khulna University, Khulna 9208, Bangladesh

[2] Department of Biochemistry and Molecular Biology, Bangabandhu Sheikh Mujibur Rahman Agricultural University, Gazipur 1706, Bangladesh

Table 1 Composition of soil sample

Soil composition	Value
Sand	20%
Silt	33%
Clay	47%
Field capacity	44%
Soil pH	7.3
Organic matter content	2.16%
Inherent salinity	0.54 dS m^{-1}
Total N	0.17%
Exchangeable P	0.0066%
Exchangeable K	0.035%
Exchangeable Ca	0.43%
Exchangeable Mg	0.048%

water holding capacity and ensures cellular water potential for physiological reactions [6]. Si strengthens cell walls and promotes bio-silicification, for alleviating various stresses. It improves root hydraulic conductivity, water use efficiency, nutrient acquisition, and photochemical efficiency [7]. Si availability in the rhizosphere is influenced by soil texture, temperature, pH, root exudation, and nutrient recycling [8]. High Si bioavailability enhances root growth, tissue strength, and stress tolerance [9]. Si-fertilized plants showed better resistance against salt stress by maintaining higher concentrations of essential nutrients, promoting macromolecule synthesis and biochemical reactions [10]. Si also increases lignin content in cell walls, enhancing mechanical strength under harsh conditions without compromising growth and physiological responses [11]. Moreover, Si can increase root water uptake through an active accumulation of soluble sugars and amino acids in plants under abiotic stress condition [12]. Application of 60 kg ha^{-1} Si combined with 100 mg L^{-1} salicylic acid resulted in a 174% augmentation in leaf area, a 91% enhancement in shoot biomass, a 28% rise in leaf relative water content, and a 112% increase in total phenol concentration in sweet basil at extreme soil moisture stress in compare to control plants [13]. Similarly, combined application of seaweed extracts 5 mL L^{-1} along with soluble Si at 60 kg ha^{-1} enhanced physiological response and fruit yield of tomato under moderate stress condition [14]. Integrated application of Si (60 kg ha^{-1}) coupled with AMF inoculation was more effective for increasing physiological traits and biomass formation along with accumulation of essential ions (K^+, Ca^{2+}, and K^+/Na^+ ratio) in salt-affected soils [15]. It has been reported that Si improves osmotic adjustment and water use efficiency for prolonging plant survival [16]. Silicon augments soil water retention and root absorption capacity for sustaining plant growth, physiological responses and yield under stressful conditions [6].

K is an essential macronutrient, supports various physiological processes, including osmoregulation, stomatal regulation, enzyme activation, and protein synthesis. It plays a crucial role in root growth, plant development, and stress tolerance by modulating physiological and biochemical processes [17]. Adequate K fertilization maintains optimal cellular functions, enhancing water balance, assimilation rate, transpiration rate, proline content, and malondialdehyde activity [18, 19]. K activates enzymes involved in ROS detoxification and osmotic regulation, improving salt tolerance and stress adaptation [20]. ROS

Table 2 Experimental factor and treatment combination

Factor A: Fertilizer doses	Factor B: Water salinity levels (dS m^{-1})
F_0: Control (Recommended dose of fertilizer RDF)	0.56
F_1: RDF + K_{30} (35 kg ha^{-1} K)	3
F_2: RDF + 60 kg ha^{-1} Si (soil)	6
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (soil)	9
F_4: RDF + 100 ppm Si (foliar)	12
F_5: RDF + K_{30} + 100 ppm Si (foliar)	

Table 3 Significance level in the two-way ANOVA of the effect of fertilizer dose (A), salinity levels (B) on root-shoot growth parameters, physiological traits, fruit quality and fruit yield of bell pepper

Traits	Fertilizer dose (A)	Salinity levels (B)	A × B
Root-shoot growth parameters			
Plant height (cm)	**	**	**
Shoot biomass (g plant^{-1})	*	*	**
Root number	**	*	ns
Actual root length (cm)	ns	*	ns
Specific root length (m g^{-1})	**	ns	ns
Deep root length (cm)	*	*	ns
Root volume (cm^3)	*	*	ns
Root biomass (g plant^{-1})	*	**	**
Root-shoot ratio (R:S)	**	ns	**
Physiological traits			
Leaf greenness (SPAD value)	**	**	**
Leaf relative water content (%)	**	*	**
Electrolyte leakage (%)	**	**	**
Proline concentration (μg g^{-1}fresh weight)	ns	**	**
Fruit quality and fruit yield			
Fruit yield (g plant^{-1})	**	**	**
Total soluble solid (°Brix)	*	*	ns
Fruit diameter (cm)	**	**	ns

**, *, and ns indicate $p < 0.01$, $p < 0.05$ and not significant, respectively serves dual functions in plants: signaling for biological processes and causing oxidative damage under stress [21]. The synergistic interaction between potassium concentration (0.5 g/l) and vinasse concentration (3 l/m^3) significantly enhanced chlorophyll index and leaf area compared to control treatments, leading to increased plant biomass and fruit yield in bell pepper [22]. Supplementing K ($NP_{100} + K_{100}$) assisted in alleviating the harmful effect of water-deficit stress, and resulted in 11%, 8%, 47%, 40%, 40%, and 42% higher leaf greenness, leaf relative water content, net photosynthetic rate, free proline content, grain yield and water productivity, respectively, in compare to control [23]

Individual effects of Si and K on bell peppers were well documented but their combined effects on root morphology, physiological attributes, and fruit yield under salt stress were less highlighted. Hence, we hypothesized that application of K and Si fertilizer would improve root growth, physiological traits and fruit yield of bell pepper under saline condition. Therefore, the study aimed to investigate the ameliorative role of Si and K on root-shoot growth, physiological responses, fruit quality and yield of bell pepper under salt stress.

2 Materials and Methods

2.1 Experimental Condition

A factorial pot experiment on bell peppers was conducted in the net house of Professor Dr. Purnendu Gain Field Laboratory, Agrotechnology Discipline, Khulna University, Bangladesh (22°48' N; 89°32' E) from October 2022 to March 2023. Well-drained fertile soil was collected from farmers' fields in Jashore, then pulverized, ground, and analyzed in the laboratory. The results of the mechanical and nutrient analysis of the experimental soils are provided below (Table 1). During the growing season, the net house temperature ranged from 22–32 °C, and relative humidity ranged from 74–86%.

2.2 Experimental Treatment and Design

The factorial experiment consisted of two factors: six fertilizer doses including control as recommended dose of fertilizer (Compost: 10 t ha^{-1}; Nitrogen: 115 kg ha^{-1}; Phosphorus: 70 kg ha^{-1}, Potassium: 125 kg ha^{-1}, Zypsum:110 kg ha^{-1}, Zinc oxide:5 kg ha^{-1}) and five levels of water salinity that presented in the Table 2. The K_{30} and Si (soil) indicated 30% additional K application of recommended dose, representing 35 kg ha^{-1} and 60 kg ha^{-1} Si over the RDF, respectively, while the Si (foliar) treatment implied application of

Table 4 Growth parameters of bell pepper influenced by the interaction between fertilizer dose and salinity levels

Fertilizer dose	Plant height (cm)					Shoot biomass (g $plant^{-1}$)				
	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}
F_0: RDF (NPK)	24 ± 0.6cA	23 ± 1.5bAB	20 ± 0.7bB	20 ± 0.6bB	19.3 ± 0.3bB	16.7 ± 0.7bA	14.7 ± 1.2bA	12.6 ± 2.7bAB	10.9 ± 2.1bAB	9.8 ± 0.1bB
F_1: RDF + K_{30} (35 kg ha^{-1} K)	28 ± 0.6bcA	24 ± 0.8bAB	22.8 ± 0.9bB	21.5 ± 0.6bB	20 ± 0.5bB	18.5 ± 0.3bAB	16.1 ± 4.3bAB	15 ± 2.2abAB	11.8 ± 0.9abB	10.2 ± 0.9bB
F_2: RDF + 60 kg ha^{-1} Si (Soil)	34 ± 1aA	32.3 ± 1.2aAB	28.7 ± 0.9aB	24.7 ± 0.3abC	23 ± 1.2abC	19.7 ± 0.4abA	17.5 ± 0.3abAB	16.4 ± 0.3abAB	14.2 ± 0.9abAB	11.8 ± 0.3abB
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	36.7 ± 0.3aA	33.7 ± 0.3aAB	29.7 ± 0.7aB	28 ± 0.6aBC	25.3 ± 0.3aC	26.2 ± 1.4aAB	23.2 ± 0.2aAB	20.5 ± 0.3aB	17.5 ± 0.7aB	15.2 ± 0.8aB
RDF + 100 ppm Si (Foliar)	26 ± 0.6cA	23 ± 0.6bAB	22 ± 0.6bB	21 ± 0.7bB	20.3 ± 0.3bB	21 ± 0.6abA	19.4 ± 0.3abAB	17 ± 0.6abAB	15.9 ± 0.6abAB	13.5 ± 0.3abB
RDF + K_{30} + 100 ppm Si (Foliar)	30 ± 0.3bA	27.8 ± 0.8bB	24 ± 0.7bB	22.9 ± 0.1bB	21 ± 0.6bB	24.2 ± 0.9aA	21.9 ± 0.1abAB	19.6 ± 0.6aAB	17.2 ± 1.2aB	14.2 ± 0.4abB

Means followed by same small case letters are statistically similar within a column and means followed by same capital letter are statistically similar within a row based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

Table 5 Individual effect of fertilizer dose and salinity levels on root number and deep root length of bell pepper

Factor	Root number	Deep root length (cm)
Fertilizer dose		
F_0: RDF (NPK)	34.8 ± 3.21b	11.67 ± 0.68b
F_1: RDF + K_{30} (35 kg ha^{-1} K)	40.67 ± 4.48b	13.67 ± 0.61b
F_2: RDF + 60 kg ha^{-1} Si (Soil)	43.73 ± 0.98b	13.57 ± 0.71ab
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	57.13 ± 1.32a	15.27 ± 0.46ab
F_4: RDF + 100 ppm Si (Foliar)	48.6 ± 1.99ab	14.8 ± 0.20ab
F_5: RDF + K_{30} + 100 ppm Si (Foliar)	45.53 ± 1.70b	14.93 ± 0.28ab
Salinity levels (dS m^{-1})		
0.54	48.27 ± 1.8a	13.83 ± 0.60a
3	43.33 ± 1.5a	13.72 ± 0.58a
6	40.33 ± 3.61ab	12.94 ± 0.44ab
9	32.56 ± 2.92b	12.89 ± 0.34ab
12	29.56 ± 2.45b	11.11 ± 0.36b

Means followed by the same letters are statistically similar within a column based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard error

100-ppm silicon solution. The experiment was arranged in a factorial completely randomized design (CRD) with three replications, in which each pot representing an individual treatment combination.

2.3 Nutrient Management

Bell pepper seeds (Orbit Red; Orbit Group, Kolkata, West Bengal, India) were procured from the local market. The seeds were surface sterilized by soaking in a 10% H_2O_2 solution, followed by rinsing in distilled water for 10 h [24]. They were then sown in earthen trays filled with a growing medium (75% cocopeat, 25% compost) and irrigated every other day with a 20–20-20 NPK fertilizer solution (200 mg L^{-1}) (Balwan Fertilizer and Chemical, Ahmedabad, Gujarat, India) starting 14 days after germination. One healthy seedling was transplanted into a brown earthen pot [50 cm (height) × 35 cm (top diameter) × 20 cm (bottom diameter)] filled with 15 kg of dry soil with 44% field capacity and inherent soil salinity of 0.54 dS m^{-1}. The recommended dose of fertilizer (RDF) was applied to all treatment combinations in which each pot received 75 g compost, 0.86 g N_2, 0.53 g P, 0.94 g K, 0.83 g Zypsum and 0.04 g ZnO [25]. A 100 ppm Si solution was sprayed with foliar twice a week from 12 days after transplanting (DAT) to full blooming stage (40 DAT). There is a thumb rule that one hectare land up to 15 cm root zone consisted of 20,00,000 kg soil [26]. We have calculated fertilizer dose for 15 kg soil for each pot by using this standard value.

2.4 Imposing Soil Salinity

A pure sodium chloride (NaCl) solution was prepared using salt (ACI Salt Ltd.; Bangladesh) and tap water, which had an initial salinity of 0.54 dS m^{-1}. Salt solutions with electrical conductivities (EC) of 3, 6, 9, and 12 dS m^{-1} were prepared by dissolving 1.7 g, 3.2 g, 4.9 g, and 7.1 g of NaCl per liter of water, respectively (EC meter; Lutron CD-4301, Taiwan) [27]. Weekly applications of 500 ml of these salt solutions began two weeks after transplanting the seedlings and continued up to five weeks. Regular irrigation was provided as needed to maintain optimal soil moisture.

2.5 Data Collection

2.5.1 Measurement of Root Morphological Traits

Root traits including root number, deep root length (cm), specific root length (m g^{-1}), root length density (RLD) (cm cm^{-3}), root volume (cm^3), root biomass (g $plant^{-1}$), shoot biomass (g $plant^{-1}$), and root-shoot ratio (R:S) were assessed from each pot. Roots were carefully removed from the pots, washed with tap water, and quantified manually. Root length was categorized into groups based on their lengths, and the average length of each group was recorded as the individual root length, from which actual root length (ARL) was determined. Root length density (RLD) was calculated as the ratio of ARL to soil root core volume following the method described by Ullah et al. [28]. Specific root length (SRL) was calculated by dividing actual root length by root biomass as per Ullah et al. [29]. Deep root length was determined as the maximum root length observed in each pot with a specific treatment combination. Root volume was calculated using the Archimedes principle for water displacement. Fresh root samples were immersed in a beaker containing 100 mL of distilled water, and the displacement of water was measured to determine root volume following the method outlined by John et al. [30]. Root and shoot biomass were determined

Table 6 Root biomass and root shoot ratio of bell pepper as influenced by the combined effect of fertilizer dose and salinity level

Fertilizer dose	Root biomass (g plant^{-1})					Root shoot ratio (R:S)				
	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}
F_0: RDF (NPK)	3.9 ± 0.7bA	3.47 ± 0.3bAB	3.02 ± 0.3bAB	2.4 ± 0.17bB	2.3 ± 0.4bB	0.23 ± 0.02bA	0.16 ± 0.02bAB	0.15 ± 0.05bAB	0.11 ± 0.05bAB	0.1 ± 0.03bB
F_1: RDF + K_{30} (35 kg ha^{-1} K)	4.5 ± 0.6abA	3.73 ± 0.7abAB	3.37 ± 0.7abAB	2.8 ± 0.2abB	2.69 ± 0.2abB	0.25 ± 0.04abA	0.18 ± 0.08abAB	0.17 ± 0.01abAB	0.17 ± 0.01abAB	0.12 ± 0.02abB
F_2: RDF + 60 kg ha^{-1} Si (Soil)	4.6 ± 0.2abA	3.83 ± 0.1abAB	3.7 ± 0.1abB	3.07 ± 0.1abAB	2.75 ± 1.2abB	0.26 ± 0.01abA	0.21 ± 0.01abAB	0.19 ± 0.01abAB	0.17 ± 0.02abAB	0.11 ± 0.03abB
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	5.73 ± 0.4aA	5.27 ± 0.2aAB	4.7 ± 0.1aAB	3.8 ± 0.3aB	3.53 ± 0.2aB	0.39 ± 0.03aA	0.34 ± 0.02aAB	0.31 ± 0.01aAB	0.27 ± 0.03aAB	0.17 ± 0.01aB
F_4: RDF + 100 ppm Si (Foliar)	4.85 ± 0.3abA	4.43 ± 0.1abAB	3.82 ± 0.2abAB	3.28 ± 0.1abAB	2.95 ± 0.2aB	0.32 ± 0.02abA	0.28 ± 0.01abAB	0.25 ± 0.02abAB	0.2 ± 0.01abAB	0.15 ± 0.03abB
F_5: RDF + K_{30} + 100 ppm Si (Foliar)	4.92 ± 0.2abA	4.63 ± 0.2abAB	3.93 ± 0.2abAB	3.45 ± 0.2abAB	3.1 ± 0.2aB	0.33 ± 0.01abA	0.3 ± 0.02abAB	0.27 ± 0.02abAB	0.21 ± 0.02abAB	0.16 ± 0.02abB

Means followed by same small case letters are statistically similar within a column and means followed by same capital letter are statistically similar within a row based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

by weighing oven-dried (at 72 °C) samples until a constant weight was achieved. The ratio of dry root weight to shoot weight for each treatment combination was used to calculate the root-shoot ratio (R: S).

2.5.2 Physiological and Biochemical Traits

During the flower initiation stage, leaf relative water content (LRWC) was assessed using the method described by Das et al. [31]. The uppermost third leaf of each plant was harvested and immediately weighed to determine its fresh weight. Each fresh leaf was then cut into small segments and immersed in distilled water for 12 h to achieve full turgidity. The weight of the fully turgid leaf segments was recorded, after which they were dried in an oven at 72 °C for 36 h to obtain their dry weight. Finally, LRWC was calculated using the following formula:

$$\text{Leaf relative water content (\%)} = \frac{(\text{FW} - \text{DW})}{(\text{TW} - \text{DW})} \times 100 \tag{1}$$

During the full blooming stage, leaf greenness (SPAD values) was measured using a portable chlorophyll meter (SPAD-502 Plus, Konica Minolta, Tokyo, Japan). Two fully expanded leaves were randomly chosen from each experimental unit, and two SPAD readings were taken per leaf. The average of these readings provided a representative SPAD value for each experimental unit. Additionally, to assess electrolyte leakage, a fresh leaf sample (0.5 g of fresh leaf discs) was cut into small pieces and placed in a test tube containing 20 ml of distilled water. The test tube was shaken continuously for 12 h to determine the initial electrical conductivity (EC1) using a meter (Eutech CON 150; Thermo Scientific Eutech Instrument, Singapore). Subsequently, the sample was heated at 60 °C for 20 min, and the final electrical conductivity (EC_2) was measured. Electrolyte leakage was calculated as the ratio of EC_1 to EC_2, expressed as a percentage according to the equation provided by Camejo et al. [32].

$$\text{EL (\%)} = \frac{\text{EC}_1}{\text{EC}_2} \times 100 \tag{2}$$

Similarly, membrane stability index was computed where EC_1 is the initial electrical conductivity at 40 °C and EC_2 is the final electrical conductivity at 100 °C.

$$\text{Membrane stability index (\%)} = (1 - \frac{\text{EC}_1}{\text{EC}_2}) \times 100 \tag{3}$$

By following sequential steps outlined by Bates et al. [33], we determined the concentration of free proline in the leaf tissue sample based on the absorbance values obtained from the spectrophotometer and the standard curve.

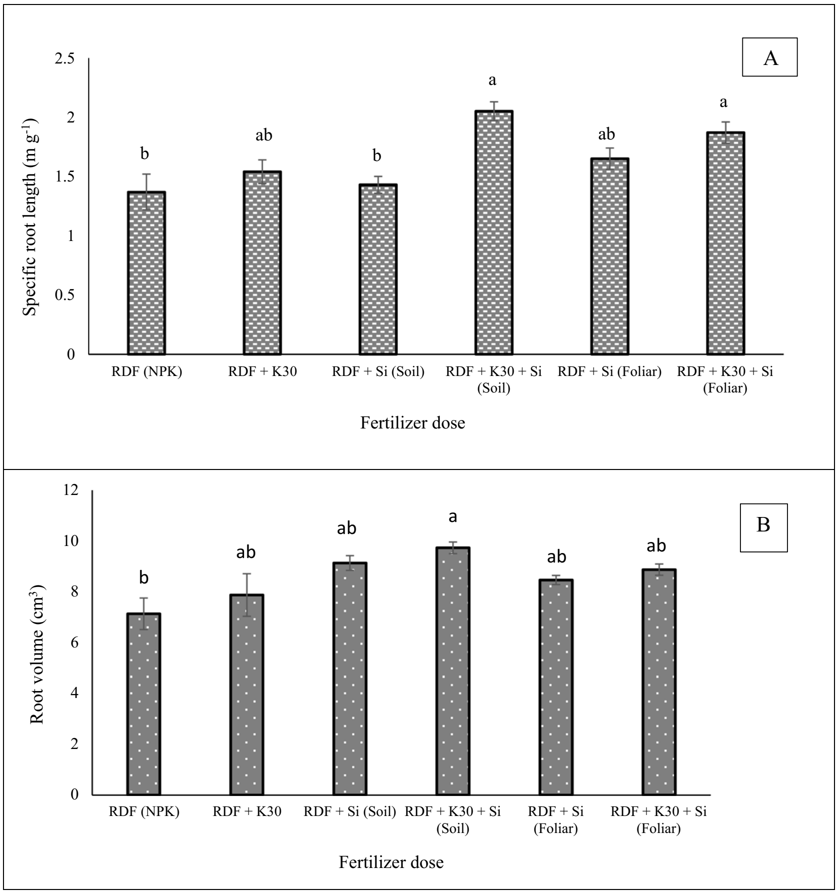

Fig. 1 Specific root length (**A**) and root volume (**B**) of bell pepper under different fertilizer doses. Means followed by the same letters are statistically similar based on Tukey's honest significant difference test at $p \leq 0.05$. Bars show means of three replications ± standard errors

2.5.3 Fruit Yield and Fruit Quality Attributes

Fruit diameter (Dp) was measured using a digital slide caliper. The pH of bell pepper pulp was determined using a desktop pH meter (HI2210; Hanna Instruments, RI, USA). After washing with distilled water, the pulp was blended, and the juice was filtered. The pH meter was then immersed in the bell pepper juice to record the pH. To determine the total soluble solids (TSS) or °Brix, a drop of pulp juice was placed on a Brix meter (Digital/Brix/RI-Check Refractometer; Reichert Technologies, Inc., Japan), and the TSS percentage as degrees Brix was obtained directly from the reading. Finally, individual fruit weights were measured and summed to obtain the total fruit weight.

2.6 Statistical Analysis

All of the collected data were subjected to a two-way analysis of variance (ANOVA) using Statistix v. 10 (Analytical Software 2105; Miller Landing Rd., Tallahassee, FL 32312, USA). Means for significant treatments effects were identified by the F test and separated by Tukey's honest significant difference test ($p < 0.05$). Data were presented based on the highest order of factorial combination that was significant in the ANOVA.

3 Results

3.1 Root-shoot Growth Parameters

The interaction between fertilizer dose and salinity levels significantly affected on plant height and shoot biomass (Table 3). Plants treated with different combinations of potassium and silicon showed increased plant height, peaking at RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) under varying salinity levels. This treatment also resulted in the highest shoot dry matter, which was 60% and 55% higher than the control at 9 and 12 dS m^{-1}, respectively (Table 4). Root number and deep root length were primarily influenced by fertilizer dose and salinity levels individually (Table 3). RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) produced the highest root number and deep root length, surpassing the control by 64% and 31%, respectively (Table 5). However, both root number and deep root length decreased with increasing salinity levels, reaching a maximum reduction of 39% and 20%, respectively, at 12

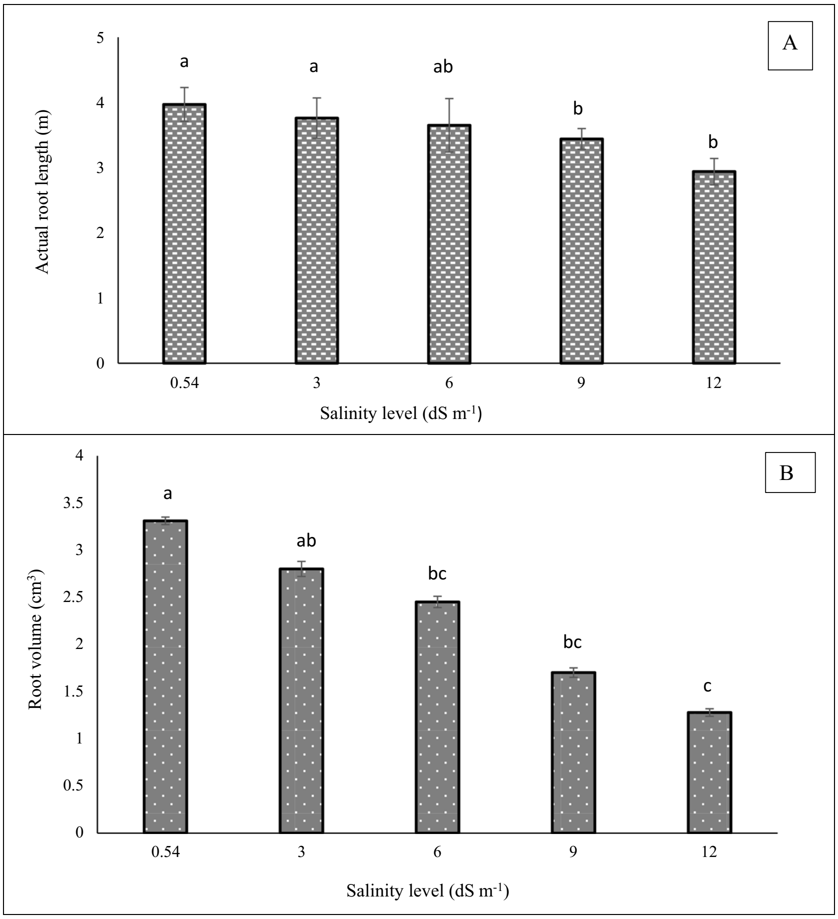

Fig. 2 Main effect of different fertilizer doses on actual root length (**A**) and root volume (**B**) of bell pepper. Means followed by the same letters are statistically similar based on Tukey's honest significant difference test at $p \leq 0.05$. Bars show means of three replications ± standard errors

dS m^{-1}. The interaction between fertilizer dose and salinity significantly impacted root biomass and root-shoot ratio. RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) consistently resulted in the highest root dry matter production and root-shoot ratio, similar to other silicon and potassium fertilizers, at 9 and 12 dS m^{-1} salinity levels (Table 6). Biomass formation increased by 20–53% compared to the control with various combinations of Si and K fertilization. Specific root length was primarily influenced by different combinations of fertilizer doses, with RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) showing the highest specific root length, 49% more than the control (Fig. 1A). The main effects of fertilizer dose and salinity levels were significant on root volume, with all fertilizer doses resulting in higher root volume compared to the control. RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) showed the maximum root volume over other treatments (Fig. 1B). Overall, root growth parameters responded similarly to salinity, with a progressive decrease observed from 0.54 dS m^{-1} to 12 dS m^{-1} Fig. 2A, B.

3.2 Physiological and Biochemical Traits

Leaf greenness (SPAD value), LRWC, and electrolyte leakage were significantly influenced by the interactive effects of different fertilizer doses and water salinity levels (Table 3). Plants treated with RDF + K_{30} (35 kg ha^{-1} K) + 100 ppm Si (foliar) exhibited approximately 16% higher leaf greenness compared to the control under 12 dS m^{-1} soil salinity, (Table 7). Foliar fertilization (RDF + K_{30} (35 kg ha^{-1} K) + 100 ppm Si) also resulted in higher LRWC at both 9 and 12 dS m^{-1} soil salinity levels, ranging from 10–65% and 13–60%, respectively. Most physiological traits declined progressively with increasing salinity levels, while electrolyte leakage increased gradually. The lowest electrolyte leakage was observed in plants treated with RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil), which was 26% lower than the control at 12 dS m^{-1} soil salinity (Table 8). The interactive effect between fertilizer dose and water salinity levels was significant for free proline content (Table 3). Proline content notably increased with higher soil salinity levels. Plants treated with RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) exhibited approximately 68% and 51% higher proline content compared to the control at 9 dS m^{-1} and 12 dS m^{-1} salinity levels, respectively (Table 9).

Table 7 Physiological traits of bell pepper as influenced by the interaction between fertilizer dose and salinity levels

Fertilizer dose	Leaf greenness (SPAD value)					Leaf relative water content (%)				
	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}
F$_0$: RDF (NPK)	62.2 ± 0.3bA	61 ± 1.5bAB	58.6 ± 0.9bAB	55.3 ± 1.8bB	51.9 ± 1.3bB	69.4 ± 4.8bA	56 ± 1.4bAB	51.1 ± 1.9bAB	48.3 ± 0.9bB	40.6 ± 3.5bB
F$_1$: RDF + K$_{30}$ (35 kg ha^{-1} K)	64 ± 0.3bA	63.1 ± 1.1abA	60.2 ± 0.1bAB	58 ± 0.3abAB	54.8 ± 0.4abB	84.4 ± 0.81abA	77.2 ± 1.56abA	63.8 ± 6.3bAB	53.2 ± 4.8bB	45.7 ± 2.1bB
F$_2$: RDF + 60 kg ha^{-1} Si (Soil)	64.25 ± 1.5abA	63.4 ± 0.7abA	62.5 ± 0.1abA	58.6 ± 1.3abAB	55 ± 1.3abB	85 ± 4.9abA	83.7 ± 4.3aA	75.8 ± 5.4abAB	65.3 ± 1.9abB	58.3 ± 1.35abB
F$_3$: RDF + K$_{30}$ + 60 kg ha^{-1} Si (Soil)	66.8 ± 1.9abA	64 ± 2.1abAB	63.3 ± 0.4abAB	60.5 ± 0.3abB	58.3 ± 0.6aB	93.8 ± 1.3aA	87.5 ± 4.12aAB	76.1 ± 2.1abAB	68.7 ± 2.76abB	60.2 ± 2.30abB
F4: RDF + 100 ppm Si (Foliar)	67.4 ± 1.1abA	65 ± 0.1abAB	63.3 ± 0.6abAB	61.3 ± 0.4aB	59.9 ± 1.4aB	87.8 ± 1.52aA	80.1 ± 4.33aAB	83.1 ± 2.6abAB	74.4 ± 6.64aB	63.6 ± 3.48aB
F$_5$: RDF + K$_{30}$ + 100 ppm Si (Foliar)	70 ± 4.5aA	67.2 ± 1.4aAB	66.8 ± 0.1aAB	63 ± 0.3aB	60.5 ± 1.3aB	102.6 ± 9.05aA	92.2 ± 1.57aAB	86.7 ± 3.85aAB	79.8 ± 3.27aB	64.8 ± 5.93aB

Means followed by same small case letters are statistically similar within a column and means followed by same capital letter are statistically similar within a row based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

3.3 Fruit Quality Attributes and Fruit Yield

Total soluble solids and fruit diameter were less affected by the interactive effect of different fertilizer doses, although both fertilizer doses and salinity levels significantly influenced these parameters (Table 3). Both total soluble solids (TSS) and fruit diameter decreased by 4% and 25%, respectively, at 12 dS m^{-1} soil salinity compared to 0.54 dS m^{-1} (Table 10). The interactive effect between various fertilizer doses and water salinity significantly influenced fruit yield (Table 3). Fruit yield decreased gradually with increasing salinity, but the application of potassium and silicon fertilizers, regardless of combination, promoted higher fruit yield compared to the control (Table 9). At 9 and 12 dS m^{-1} salinity levels, Si-K treated plants exhibited 23–56% and 21–41% higher fruit yield, respectively, compared to the control. RDF + K$_{30}$ (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) resulted in the maximum fruit yield, followed by RDF + K$_{30}$ (35 kg ha^{-1} K) + 100 ppm Si (Foliar), outperforming other combinations.

4 Discussion

Soil salinity represents a significant environmental constraint that adversely affects various physiological and biochemical processes crucial for optimal crop growth and yield. Soluble salts disrupt numerous plant functions, including root growth, carbon fixation, nitrogen metabolism, nutrient uptake, stomatal conductance, transpiration, and assimilate partitioning [34, 35]. Root and shoot biomass are reliable indicators of plant tolerance against salt stress [36]. In the current study, it was observed that plant height, shoot biomass, and root biomass were significantly increased in silicon-treated plants compared to the control (Table 4). This enhancement can be attributed to rapid cell division and elongation at the apical meristem for promoting both root and leaf length, consequently increasing surface area. The larger leaf surface area might be facilitated greater carbon fixation through photosynthesis, leading to higher shoot biomass [37]. These findings align with previous studies by Medhat et al. [38] and Lob et al. [39], who were demonstrated the significant influence of silicon on plant biomass formation. Additionally, it was evident in this experiment that root biomass, root volume, and deep root length were significantly increased by the combined application of Si and K fertilization (Table 6). Salt stress typically reduces the water potential of the root medium, resulting in lower root water uptake and restricted upward water movement [40]. But Si application reduces the osmotic potential in the rhizosphere by increasing root soluble sugars, thereby favoring water uptake to maintain optimal physiological and biochemical reactions in plants [16]. Moreover, the enhanced

Table 8 Electrolyte leakage of bell pepper as influenced by the interaction between fertilizer doses and salinity levels

Fertilizer dose	Electrolyte leakage (%)				
	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}
F_0: RDF (NPK)	70.8 ± 0.2aB	74.5 ± 2.5abB	79 ± 1.93abAB	84.3 ± 2.8abAB	90.6 ± 0.57aA
F_1: RDF + K_{30} (35 kg ha^{-1} K)	63.5 ± 2.9abB	65.2 ± 3.6abB	67.9 ± 3.3abAB	74.7 ± 0.5abAB	84 ± 3.75abA
F_2: RDF + 60 kg ha^{-1} Si (Soil)	55.4 ± 0.8abB	61.2 ± 1.6bB	70.6 ± 0.8abAB	76.1 ± 0.8abAB	79 ± 0.37abA
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	53 ± 0.9bB	55.8 ± 3.6bB	66.5 ± 2.78bAB	68.3 ± 1.5bAB	71.7 ± 2.5bA
F_4: RDF + 100 ppm Si (Foliar)	71.3 ± 6.7aB	79 ± 1.3aB	85.1 ± 3.98aAB	86.1 ± 1.38aAB	89.3 ± 5.41aA
F_5: RDF + K_{30} + 100 ppm Si (Foliar)	66.9 ± 0.3abB	69.3 ± 0.5abB	77.7 ± 3.4abAB	83.2 ± 8.9abAB	87.1 ± 3.47abA

Means followed by same small case letters are statistically similar within a column and means followed by same capital letters are statistically similar within a row based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

bioavailability of silicon in the rhizosphere promotes soil water holding capacity, thereby stimulating root number, root volume, and root biomass through increased rooting activity [41, 42]. In the current study, the regulatory roles of Si and K were highly evident in which the most evaluated root traits outperforming the control. Particularly, RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) fertilized plants exhibited higher root number, deep root length, root biomass, and root-shoot ratio under varying levels of salt stress (Tables 5 and 6). This proliferation of root traits under Si fertilization suggests that silicon improves root hydraulic conductivity and root activity, resulting an efficient water and mineral absorption from the soil, followed by assimilation of more dry matter production under salt stress [7]. These photosynthates are preferentially allocated for root development and root exudation, enabling plants to alleviate stress and enhance tolerance to abiotic stress [43]. Our findings closely correlate with Kuhla et al. [6], who reported that Si deposition on the inner tangential wall of roots enhances tissue mechanical strength, thereby conferring protection against oxidative damage and promoting root growth with tolerance index against abiotic stress [44]. Similarly, Si supplementation (60 kg ha $^{-1}$) enhanced morphophysiological responses, tolerance capacity and fruit yield more than two folds over control even at extreme saline condition [45]. Combined application of nitric oxide and 2 mM silicon promoted stem diameter, biomass weight, proline concentration and MDA content in bell pepper leaves under salt stress [36] (Badem et al. 2022).

The results of the current study indicated that SPAD value and LRWC were significantly reduced with increasing salinity levels regardless of fertilizer dosage. However, the combined application of Si and K fertilizers notably improved these parameters compared to the control (Table 7). Actually, salinity induces chlorophyll degradation and structural damage to cell membranes, as evidenced by the decline in leaf greenness with increasing salinity was observed in our study (Table 7). The presence of salt stress triggers the production of reactive oxygen species (ROS), leading to the deterioration of proteins, nucleic acids, and cell membranes [46]. ROS, generated as metabolic byproducts through partial oxygen reduction, inflicts oxidative harm on cellular components under stress conditions, while also serving as signaling molecules under normal circumstances [47]. It's widely recognized that the application of varying doses of beneficial elements (Si) can enhance morphological and physiological traits to mitigate salt stress in Solanaceous vegetables, particularly bell peppers. Furthermore, supplementing plants with Si and K can bolster resistance to a spectrum of abiotic stresses. In our current investigation, we observed a significant reduction in root growth, physiological traits, and yield of bell peppers under different levels of salinity. However, the application of various combinations of Si and K helped to alleviate the detrimental effects of salt stress on bell pepper. Salt stress also induces moisture stress in rhizosphere, which promotes chlorophyll degradation by activating the enzyme chlorophyllase. Si-fertilized plants exhibited higher leaf greenness, possibly due to significant inhibition of this enzyme activity. Studies have shown that silicon protects chlorophyll molecules by enhancing pigment system stability and thylakoid membrane integrity, leading to a higher net photosynthetic rate [48]. It was reported that 60 kg ha $^{-1}$ Si fertilization was effectively promoted net photosynthetic rate, irrigation water productivity and fruit yield in cucumber Application of 60 kg ha^{-1} Si combined with 100 mg L^{-1} salicylic acid resulted enhancement of leaf area, shoot biomass, LRWC and total phenol content by 174%, 91%, 28% and 112% in sweet basil at extreme soil moisture stress in compare to control plants [13]. Similarly, combined application of seaweed extracts 5 mL L^{-1} along with soluble Si at 60 kg ha^{-1} enhanced physiological response and fruit yield of tomato under moderate stress condition [14]. It has been found that among different soil application doses of Si, 60 kg ha $^{-1}$ resulted in 217–293%, 198–307%, and 11–33% enhancement in fruit yield, irrigation water productivity, and net photosynthetic rate, respectively, over the control [15].

Osmotic regulation stands as a critical metabolic adaptation for most crop plants to mitigate the adverse effects of salt stress by reducing cellular osmotic potential through the synthesis of various organic and inorganic osmolytes in the cytoplasm [49]. The current study revealed higher concentrations of fruit TSS and leaf proline in all combinations of Si-K treated plants compared to the control, even at a salinity level of 12 dS m^{-1} (Table 9). These findings indicate that proline content gradually increased with rising salt stress levels and was significantly influenced by Si and K fertilization. Our results suggest that plants treated with RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) exhibited approximately 68% and 51% higher proline content compared to control at salinity levels of 9 dS m^{-1} and 12 dS m^{-1}, respectively (Table 9). Si led to the accumulation of proline, soluble sugars, and glycine betaine in plants, resulting in enhanced osmotic adjustment with improved turgidity. Proline serves as a compatible organic osmolyte, acting as a free radical scavenger to protect biomolecules against oxidative stress [50]. The biosynthesis of various osmolytes, including proline, soluble sugars, and glycine betaine, drives osmotic adjustment to counteract the lethal effects of oxidative damage by scavenging ROS, maintaining membrane integrity, and stabilizing enzymes [51]. Proline accumulation is associated with stress tolerance and it was reported that stress-tolerant plants exhibit higher levels of free proline concentration than stress-sensitive ones [52]. Proline acts as a stress marker and compatible osmolyte, accumulating exponentially in plants under stressful conditions to maintain internal water balance in plant tissues [18, 53, 55]. Moreover, improved root biomass by 38% and individual fruit weight by 21% and lower proline accumulation with strong antioxidative defense system induced by standard fertilizer dose along with organic matter application and silicon supplementation (60 kg ha^{-1}) implied by nullifying the lethal effect of oxidative damage [54, 56]. Foliar application of silicon led to augments concentrations of chlorophyll concentration and mineral nutrients, water status, and fruit yield of sweet pepper plants under sat stress [18, 55].

Potassium (K) serves as a crucial osmotic regulator in plant physiology, maintaining osmotic adjustment, membrane stability, cytoplasmic homeostasis, protein synthesis, and enzyme activation [54, 56, 57]. During salt stress, elevated concentrations of Na^+ and Cl^- in root epidermal tissue can disrupt metabolic processes in plants. Therefore, it's essential to maintain cytosolic K^+ levels within a certain threshold to adjust tissue ionic balance [58]. K-mediated antioxidant enzyme activities, such as superoxide dismutase (SOD), catalase (CAT), and peroxidase (POD), play a significant role in suppressing ROS formation in plant cells. Additionally, adequate tissue K concentration stabilizes the photosynthetic electron transport system and inhibits the activities of nicotinamide adenine dinucleotide phosphate (NADPH) oxidases, thus reducing ROS generation during salt stress [59]. Higher doses of K have been shown

Table 9 Interactive effect of fertilizer dose and salinity levels on proline concentration and fruit yield of bell pepper

Fertilizer dose	Proline concentration (µg g^{-1} fresh weight)					Fruit yield (g $plant^{-1}$ fresh weight)				
	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}	0.54 dS m^{-1}	3 dS m^{-1}	6 dS m^{-1}	9 dS m^{-1}	12 dS m^{-1}
F_0: RDF (NPK)	130.3 ± 10.1bB	140.3 ± 1.5bAB	195 ± 16.3bAB	218 ± 10.1bAB	258.3 ± 12.4bA	211.3 ± 10.7bAB	187 ± 3.8bAB	177.6 ± 2.2bAB	156.3 ± 4.4bB	138.3 ± 11.1bB
F_1: RDF + K_{30} (35 kg ha^{-1} K)	216 ± 1.8abB	255.3 ± 3.7abAB	285 ± 8.7abAB	322 ± 7.6abAB	356 ± 13.1abA	260 ± 12.8abB	237.7 ± 9.2bAB	212.7 ± 8.9abAB	191.7 ± 10abB	173.3 ± 7.3abB
F_2: RDF + 60 kg ha^{-1} Si (Soil)	237.7 ± 3.8abB	244.3 ± 9.5abB	301.7 ± 0.8abAB	352.3 ± 3.5aAB	369 ± 7.5abA	287 ± 5.86aA	250.7 ± 9.2abAB	236.3 ± 12.2aAB	198.7 ± 8.3abB	171.7 ± 9.3abB
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	257 ± 1.5aB	265.3 ± 5.2aB	345 ± 9.3aAB	366 ± 3.21aAB	389.3 ± 9.4aA	312.7 ± 6.3aA	295.3 ± 7.5aAB	252 ± 12.9aB	243.7 ± 5.7aBC	195.3 ± 3.8aC
F_4: RDF + 100 ppm Si (Foliar)	213 ± 6.9abB	242.3 ± 2.6abAB	274.7 ± 7.3abAB	319 ± 4.7abAB	350 ± 11.2abA	266 ± 5.3abA	250 ± 8.3abA	228.7 ± 5.5abAB	193 ± 5abB	167.3 ± 6.6abB
F_5: RDF + K_{30} + 100 ppm Si (Foliar)	239 ± 1.2abB	261 ± 3.2abAB	326.7 ± 3.18aAB	365.7 ± 10.7aA	370 ± 5.3abA	290.3 ± 4.8aA	276 ± 3.5abA	240.7 ± 8.5aAB	214.3 ± 9.4abB	180.2 ± 5.7abB

Means followed by same small case letters are statistically similar within a column and means followed by same capital letter are statistically similar within a row based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

Table 10 Individual effect of fertilizer dose and salinity levels on total soluble solid and bell pepper fruit diameter of bell pepper

Treatment	Total soluble solid (°Brix)	Fruit diameter (cm)
Fertilizer doses		
F_0: RDF (NPK)	9.13 ± 0.17b	4.17 ± 0.22a
F_1: RDF + K_{30} (35 kg ha^{-1} K)	9.87 ± 0.15ab	4.09 ± 0.23a
F_2: RDF + 60 kg ha^{-1} Si (Soil)	9.25 ± 0.18b	4.24 ± 0.14a
F_3: RDF + K_{30} + 60 kg ha^{-1} Si (Soil)	10.47 ± 0.19a	4.07 ± 0.19a
F_4: RDF + 100 ppm Si (Foliar)	9.97 ± 0.19ab	3.77 ± 0.21ab
F_5: RDF + K_{30} + 100 ppm Si (Foliar)	9.5 ± 0.19b	3.41 ± 0.19b
Salinity levels (dS m^{-1})		
0.54	9.39 ± 0.14ab	4.4 ± 0.09a
3	9.67 ± 0.12a	4.29 ± 0.11a
6	9.67 ± 0.11a	4.15 ± 0.2ab
9	9.05 ± 0.19ab	3.67 ± 0.17b
12	9.03 ± 0.20b	3.28 ± 0.21b

Means followed by the same letters are statistically similar within a column based on Tukey's honest significant difference test at $p < 0.05$; data are means of three replications ± standard errors

to improve non-structural carbohydrate (NSC) contents, photosynthetic pigment levels, antioxidative activity, and decrease lipid peroxidation. The results of this study demonstrate that RDF + K_{30} (35 kg ha^{-1} K) + 60 kg ha^{-1} Si (soil) significantly influenced root morphological and physiological traits, including root biomass, root volume, root-shoot ratio, leaf greenness, and LRWC depicted that K enhances water and nutrient uptake from the rhizosphere by penetrating roots from deeper soil layers, ultimately enhancing the plant's ability to withstand salt stress [54]. Improvements in morpho-physiological and yield performance in crop plants are closely linked to K-mediated detoxification of ROS, activation of antioxidative defense systems, and biosynthesis of osmolytes to cope up with the adverse environments [18, 55, 60, 61]. Higher fruit yield in bell pepper with K fertilization can be attributed to increased chlorophyll biosynthesis, improved stomatal regulation, enhanced enzyme activity, and greater biomass formation, resulting in increased carbohydrate accumulation and translocation for fruit formation [62, 63]. K fertilization also enhances nutrient uptake, luxurious vegetative growth to prolong the fruit formation period and increase fruit yield [64]. Moreover, K plays a significant role in activating ATP synthase enzyme and regulating stomatal aperture to optimize carbon fixation and the utilization of photo-assimilates for fruit formation [65]. Additionally, potassium regulates carbohydrate partitioning, crucial for improving assimilate remobilization from source to sink under suboptimal environments [66–68]. These findings align closely with those of Das et al. [5], who reported that NP_{100} + K_{100} exhibited better stomatal conductance, net photosynthetic rate, and yield under arid environments. In the present study, salt stress induced a significant decrease in shoot biomass and fruit yield across all fertilizer combinations, and plants fertilized with RDF + K_{30} + 60 kg ha^{-1} Si (soil) had 41% higher fruit yield over the control at severe salt stress (12 dS m^{-1}), which was also statistically at par with almost all other combination of fertilizers, indicating that both K and Si had a positive role in maintaining net photosynthesis (P_n) under salt stress. This improved P_n of Si-fertilized plants under salt stress might be due to a Si-mediated increase of intercellular CO_2 concentration of leaf ensuring an ample supply of CO_2 for optimum photosynthesis, which is a pre-requisite for fruit formation [69]. This claim has been also supported by Kang et al. [70] who mentioned that photosynthesis is the physiological basis of plant growth and development and Si improves drought tolerance by reducing oxidative damage of lipid and protein with a significant rise in P_n. Therefore, additional Si and K fertilization either in the soil or foliar application along with standard fertilizer doses, significantly augmented root growth and fruit yield of bell pepper under salt stress.

5 Conclusion

Our study demonstrated that various combinations of Si and K significantly enhanced root-shoot morphological traits and fruit yield in bell pepper compared to the control. For instance, RDF + K_{30} + 60 kg ha^{-1} Si (soil) application resulted in 64%, 31%, and 53% higher root number, deep root length, and root biomass, respectively, over control. Leaf proline accumulation increased gradually with rising salinity levels in which plants treated with RDF + K_{30} + 60 kg ha^{-1} Si (soil) accumulated 51% more proline, followed by 43% in foliar application of silicon (RDF + K_{30} + 100 ppm Si) at 12 dS m^{-1} salinity level. Moreover RDF + K_{30} + 60 kg ha^{-1} Si (soil)fertilized plants produced approximately 56% and 41% higher fruit yield at salinity levels of 9 and 12 dS m^{-1}, respectively. Based on our research findings, it can be concluded that soil application of silicon at 60 kg ha^{-1} combine with a 30% additional application of potassium, along with standard fertilizer dose, significantly promoted root growth and fruit yield of bell pepper even at 12 dS m^{-1} salinity levels. Thus, combined application of Si and K showed ameliorative potential and minimized the adverse impacts of salt stress on root growth, physio-biochemical traits, and fruit yield of bell pepper.

Acknowledgements The authors would like to express their gratitude to the Research and Innovation Center, Khulna University, Khulna, Bangladesh for funding and Agrotechnology Discipline, Khulna University, Khulna, Bangladesh for providing necessary logistic support during the experiment.

Author Contributions Fabiha Bushra, Disha Mallick, Md. Bappy Hossain and Sumon Chandro Pal were prepared the initial manuscript. Dr. Prosanta Kumar Dash and Dr. Abdul Mannan reviewed the initial manuscript carefully. Dr. Nure Kutubul Islam contributed by throughly review and figure preparation. Dr. Debesh Das supervised the whole research and suggested for manuscript preparation followed by review rigorously.

Funding It is declared that Research and Innovation Center, Khulna University, Bangladesh provided funding for this research expenditure.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing Interests The authors declare no competing interests.

References

1. Yilmaz K, Akinci IE, Akinci S (2004) Effect of salt stress on growth and Na, K contents of pepper (*Capsicum annuum* L.) in germination and seedling stages. Pak J Biol Sci 7:606–610
2. Wasaya A, Zhang X, Fang Q, Yan Z (2018) Root phenotyping for drought tolerance: a review. Agronomy 8(11):241
3. Ullah H, Rahimi AZ, Datta A (2019) Growth and yield of lowland rice as influenced by potassium application and cultivation method under alternate wetting and drying water regime. J Plant Nutr 42(13):1529–1542
4. Rabbi SMF, Tighe MK, Warren CR, Zhou Y, Denton MD, Barbour MM, Young IM (2021) High water availability in drought tolerant crops is driven by root engineering of the soil microhabitat. Geoderma 383:114738
5. Das D, Ali MA, Sarkar TA, Ali MY (2017) Germination and seedling growth of indigenous aman rice under salt stress. J Bangladesh Agric Univ 15(2):182–187
6. Kuhla J, Pausch J, Schaller J (2021) Effect on soil water availability, rather than silicon uptake by plants, explains the beneficial effect of silicon on rice during drought. Plant Cell Environ 44:3336–3346
7. Zargar SM, Mahajan R, Bhat JA, Nazir M, Deshmukh R (2019) Role of silicon in plant stress tolerance: opportunities to achieve a sustainable cropping system. 3 Biotech 9(3):73
8. Ahmed M, Khurshid Y (2011) Does silicon and irrigation have impact on drought tolerance mechanism of sorghum? Agric Water Manag 98(12):1808–1812
9. Ahanger MA, Bhat JA, Siddiqui MH, Rinklebe J, Ahmad P (2020) Integration of silicon and secondary metabolites in plants: a significant association in stress tolerance. J Exp Bot 71(21):6758–6774
10. Alam A, Hariyanto B, Ullah H, Salin KR, Datta A (2021) Effects of silicon on growth, yield and fruit quality of cantaloupe under drought stress. Silicon 13:3153–3162
11. Zhao D, Xu C, Luan Y, Shi W, Tang Y, Tao J (2021) Silicon enhances stem strength by promoting lignin accumulation in herbaceous peony (*Paeonia lactiflora Pall.*). Int J Biol Macromol 190:769–779
12. Gomaa MA, Kandil EE, El-Dein AAMZ, Abou-Donia MEM, Ali HM, Abdelsalam NR (2021) Increase maize productivity and water use efficiency through application of potassium silicate under water stress. Sci Rep 11:224
13. Biswas A, Ullah H, Himanshu SK, García-Caparrós P, Chungloo D, Praseartkul P, Tisarum R, Cha-um S, Datta A (2024) Morpho-physio-biochemical responses of sweet basil plants to integrated application of silicon and salicylic acid under water supply restrictions. Silicon. https://doi.org/10.1007/s12633-024-03123-4
14. Ahmed M, Ullah H, Attia A et al (2023) Interactive effects of *Ascophyllum nodosum* seaweed extract and silicon on growth, fruit yield and quality, and water productivity of tomato under water stress. Silicon 15:2263–2278
15. Islam ATMT, Ullah H, Himanshu SK et al (2023) The interactive effects of silicon and arbuscular mycorrhizal fungi on growth, physio-biochemical traits, and cob yield of baby corn plants under salt stress. Silicon 15:4457–4471
16. Zhu Y, Gong H (2014) Beneficial effects of silicon on salt and drought tolerance in plants. Agron Sustain Dev 34:455–472
17. Ragel P, Raddatz N, Leidi EO, Quintero FJ, Pardo JM (2019) Regulation of K^+ nutrition in plants. Front Plant Sci 10:281
18. Zain NAM, Ismail MR (2016) Effects of potassium rates and types on growth, leaf gas exchange and biochemical changes in rice (*Oryza sativa*) planted under cyclic water stress. Agric Water Manag 164:83–90
19. Das D, Basar NU, Ullah H, Salin KR, Datta A (2021) Interactive effect of silicon and mycorrhizal inoculation on growth, yield and water productivity of rice under water-deficit stress. J Plant Nutr 44:2756–2769
20. Rejeb KB, Abdelly C, Savouré A (2014) How reactive oxygen species and proline face stress together. Plant Physiol Biochem 80:278–284
21. Zahoor R, Dong H, Abid M, Zhao W, Wang Y, Zhou Z (2017) Potassium fertilizer improves drought stress alleviation potential in cotton by enhancing photosynthesis and carbohydrate metabolism. Environ Exp Bot 137:73–83
22. Rady MS, Ghoneim IM, Feleafel MN et al (2024) Potassium silicate and vinasse enhance biometric characteristics of perennial sweet pepper (*Capsicum annuum*) under greenhouse conditions. Sci Rep 14:11248
23. Das D, Ullah H, Tisarum R, Cha-um S, Datta A (2023) Morpho-physiological responses of tropical rice to potassium and silicon fertilization under water-deficit stress. J Soil Sci Plant Nutr 23:220–237
24. Mukherjee S, Dash PK, Das D, Das S (2023) Growth, yield and water productivity of tomato as influenced by deficit irrigation water management. Environ Process 10:10
25. Krishi Projukti Hatboi (Handbook of Agrotechnology) 2nd Edition, Bangladesh Agricultural Research Institute, Gazipur, Bangladesh

26. Hepperly P (2020) Re: How many kilograms of soil are in one hectare? Could anyone explain how to calculate biochar from grams/kg soil to kg/ha? Retrievedfrom:https://www.researchgate.net/post/How_many_kilograms_of_soil_are_in_one_hectare_Could_anyone_explain_how_to_calculate_biochar_from_grams_kg_soil_to_kg_ha/5fd76b8e62d52f03786b42f4/citation/download
27. Adhikary D, Das D, Ali MY, Ullah H, Datta A (2022) Growth, grain yield, and water productivity of traditional rice landraces from coastal Bangladesh, as affected by salt stress. J Crop Improv 37(1):60–73
28. Ullah H, Datta A, Shrestha S, Ud Din S (2017) The effects of cultivation methods and water regimes on root systems of drought tolerant (RD6) and drought-sensitive (RD10) rice varieties of Thailand. Arch Agron Soil Sci 63:1198–1209
29. Ullah H, Luc PD, Gautam A, Datta A (2018) Growth, yield and silicon uptake of rice (*Oryza sativa*) as influenced by dose and timing of silicon application under water-deficit stress. Arch Agron Soil Sci 64:318–330
30. John TH, John GM, James TF (1994) Volume displacement provides a quick and accurate way to quantify new root production. New Mexico State University, Department of Agronomy and Horticulture, Mora Research Center, Box 359, Mora, NM 87732
31. Das D, Basar NU, Ullah H, Attia A, Salin KR, Datta A (2022) Growth, yield and water productivity of rice as influenced by seed priming under alternate wetting and drying irrigation. Arch Agro Soil Sci 68(11):1515–1529
32. Camejo D, Rodriguez P, Morales MA, Amico JMD, Torrecillas A, Alarcon JJ (2005) High temperature effects on photosynthetic activities of two tomato cultivars with different heat susceptibility. Plant Physiol 162:281–289
33. Bates LS, Waldren RP, Teare ID (1973) Rapid determination of free proline for water-stress studies. Plant Soil 39:205–207
34. Lucini L, Rouphael Y, Cardarelli M, Canguier R, Kumar P, Colla G (2015) The effect of a plant-derived biostimulant on metabolic profiling and crop performance of lettuce grown under saline conditions. Sci Hort 182:124–133
35. Yin Y, Li S, Liao W, Lu Q, Wen X, Lu C (2010) Photosystem II photochemistry, photoinhibition and the xanthophyll cycle in heat stressed rice leaves. Plant Physiol 167:959–966
36. Badem A, Söylemez S (2022) Effects of nitric oxide and silicon application on growth and productivity of pepper under salinity stress. J King Saud Univ Sci 34(6):102189
37. Jufri AF, Sulistyono E (2016) Studies on the effects of silicon and antitranspirant on chili pepper (*Capsicum annuum* L.) growth and yield. Eur J Sci Res 137:5–10
38. Medhat A, Aziz A, Geeth RH (2018) Effect of foliar spray with some silicon sources and paclobutrazol on growth, yield and fruit quality of sweet pepper (*Capsicum annuum* L.) plants under high-temperature conditions. Egypt J Agric Res 96(2):577–593
39. Lob S, Sa'ad NS, Ibrahim NF, Soh NC, Shah RM, Zaudin MSH (2023) Enhanced growth of chili (*Capsicum annuum* L.) by silicon nutrient application in fertigation system. Malays Appl Biol 52(2):13–19
40. Munns R, Tester M (2008) Mechanisms of salinity tolerance. Annu Rev Plant Biol 59(1):651–681
41. Schaller J, Cramer A, Carminati A, Zarebanadkouki M (2020) Biogenic amorphous silica as main driver for plant available water in soils. Sci Rep 10:2424
42. Kim Y, Chung YS, Lee E, Tripathi P, Heo S, Ki KH (2020) Root response to drought stress in rice (*Oryza sativa* L.). J Mol Sci 21(4):1513
43. Soundararajan P, Manivannan A, Ko CH, Jeong BR (2018) Silicon enhanced redox homeostasis and protein expression to mitigate the salinity stress in rosa hybrida 'rock fire.' J Plant Growth Regul 37(1):16–34
44. Ahmed M, Ullah H, Attia A, Tisarum R, Cha-um S, Datta A (2023) Interactive effects of *Ascophyllum nodosum* seaweed extract and silicon on growth, fruit yield and quality, and water productivity of tomato under water stress. Silicon 15(5):2263–2278
45. Lubitz W, Chrysina M, Cox N (2019) Water oxidation in photosystem II. Photosynthetic Res 142:105–125
46. Huang S, Leng G, Huang Q, Xie Y, Liu S, Meng E, Li P (2017) The asymmetric impact of global warming on US drought types and distributions in a large ensemble of 97 hydro-climatic simulations. Sci Rep 7(1):5891
47. Feng JP, Shi QH, Wang XF, Wei M, Yang FJ, Xu H (2010) Silicon supplementation ameliorated the inhibition of photosynthesis and nitrate metabolism by cadmium toxicity in Cucumis sativus L. Sci Hortic 123:521–530
48. Alam AU, Ullah H, Himanshu SK, Tisarum R, Praseartkul P, Cha-um S, Datta A (2024) Effect of silicon application method on morpho-physio-biochemical traits of cucumber plants under drought stress. Silicon. https://doi.org/10.1007/s12633-024-03058-w
49. Begum N, Ahanger MA, Zhang L (2020) AMF inoculation and phosphorus supplementation alleviates drought induced growth and photosynthetic decline in Nicotiana tabacum by up-regulating antioxidant metabolism and osmolyte accumulation. Environ Exp Bot 176:104088
50. Kaur G, Asthir B (2015) Proline: a key player in plant abiotic stress tolerance. Biol Plant 59(4):609–619
51. Kumar S, Li G, Yang J, Huang X, Ji Q, Liu Z, Ke W, Hou H (2021) Effect of salt stress on growth, physiological parameters, and ionic concentration of water dropwort (*Oenanthe javanica*) cultivars. Front Plant Sci 12:660409
52. Abdelaziz ME, Kim D, Ali S, Fedorof NV, Al-Babili S (2017) The endophytic fungus *Piriformospora indica* enhances *Arabidopsis thaliana* growth and modulates Na^+/K^+ homeostasis under salt stress conditions. Plant Sci 263:107–115
53. Liang W, Zhang Z, Wen X, Liao Y, Liu Y (2017) Effect of non-structural carbohydrate accumulation in the stem pre-anthesis on grain filling of wheat inferior grain. Field Crop Res 211:66–76
54. Chakma R, Ullah H, Sonprom J et al (2023) Effects of silicon and organic manure on growth, fruit yield, and quality of grape tomato under water-deficit stress. Silicon 15:763–774
55. Abdelaal KAA, Mazrou YSA, Hafez YM (2020) Silicon foliar application mitigates salt stress in sweet pepper plants by enhancing water status, photosynthesis, antioxidant enzyme activity and fruit yield. Plants 9(6):733
56. Almeida DM, Oliveira MM, Saibo NJM (2017) Regulation of Na^+ and K^+ homeostasis in plants: towards improved salt stress tolerance in crop plants. Genet Mol Biol 40:326–345
57. Raza MAS, Saleem MF, Shah GM, Khan IH, Raza A (2014) Exogenous application of glycinebetaine and potassium for improving water relations and grain yield of wheat under drought. J Soil Sci Plant Nutr 14:348–364
58. Shabala S, Bose J, Fuglsang AT, Pottosin I (2016) On a quest for stress tolerance genes: membrane transporters in sensing and adapting to hostile soils. J Exp Bot 67:1015–1031
59. Jan AU, Hadi F, Midrarullah NMA, Rahman K (2017) Potassium and zinc increase tolerance to salt stress in wheat (*Triticum aestivum* L.). Plant Physiol Biochem 116:139–149
60. Römheld V, Kirkby EA (2010) Research on potassium in agriculture: needs and prospects. Plant Soil 335:155–180
61. Demidchik V, Straltsova D, Medvedev SS, Pozhvanov GA, Sokolik A, Yurin V (2014) Stress-induced electrolyte leakage: the role of K+-permeable channels and involvement in programmed cell death and metabolic adjustment. J Exp Bot 65(5):1259–1270
62. Jatav KS, Agarwal RM, Tomar NS, Tyagi SR (2014) Nitrogen metabolism, growth and yield responses of wheat (*Triticum*

aestivum L.) to restricted water supply and varying potassium treatments. Indian Bot Soc 93:177–189

63. Sustr M, Soukup A, Tylova E (2019) Potassium in root growth and development. Plants 8(10):10
64. Islam A, Muttaleb A (2016) Effect of potassium fertilization on yield and potassium nutrition of boro rice in a wetland ecosystem of Bangladesh. Arch Agron Soil Sci 62:1530–1540
65. Hasanuzzaman M, Bhuyan MHMB, Nahar K, Hossain MS, Mahmud J, Hossen Al, Masud MS, Moumita AAC, Fujita M (2018) Potassium: a vital regulator of plant responses and tolerance to abiotic stresses. Agronomy 8(3):31
66. Ye T, Li Y, Zhang J, Hou W, Zhou W, Lu J, Xing Y, Li X (2019) Nitrogen, phosphorus and potassium fertilization affects the flowering time of rice (*Oryza sativa* L). Glob Ecol Conserv 20:e00753
67. Li Z, Li Z, Letuma P, Zhao H, Zhang Z, Lin W, Chen H, Lin W (2018) A positive response of rice rhizosphere to alternate moderate wetting and drying irrigation at grain filling stage. Agric Water Manag 207:26–36
68. Pal SC, Hossain MB, Mallick D, Bushra F, Abdullah SMR, Dash PK, Das D (2023) Combined use of seaweed extract and arbuscular mycorrhizal fungi for alleviating salt stress in bell pepper (*capsicum annuum* L.). Scientia Horticulturae 325:112597
69. Li X, Zhang X, Liu G, Tang Y, Zhou C, Zhang L, Lv J (2020) The spike plays important roles in the drought tolerance as compared to the flag leaf through the phenylpropanoid pathway in wheat. Plant Physiol Biochem 152:100–111
70. Kang J, Zhao W, Zhu X (2016) Silicon improves photosynthesis and strengthens enzyme activities in the C_3 succulent xerophyte *Zygophyllum xanthoxylum* under drought stress. Plant Physiol 199:76–86